GROUND IMPROVEMENT BY USING STONE COLUMNS

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Abstract— As more and more land becomes subject to urban and industrial development so good construction sites are difficult to find. In situ ground characteristics of construction site are different from those desired and, almost always, form ideal for a designated need. In many a situations in order to satisfy client's desire the engineer may be compelled to construct structures at location selected for reasons other than ground support conditions. Thus it has become increasingly important for the engineer to know the extent to which alterations have to make for the construction of an intended structure at a stipulated site. Ground improvement in this broadest sense is the alteration of any property of a soil or rock to improve its engineering performance. This may be a permanent measure to improve the complete facility or a temporary process to allow the construction of a facility. This paper review a widely used ground improvement technique stone columns also known as granular column or granular pile. Numerous instances arise where the soils at shallow depths are inadequate for support of proposed structure in response to such needs special technique for the in-place treatment of ground has been developed called stone columns. This technique is used for silty and clayey soils who have very low bearing capacity. This report covers the study of designing of stone columns, failure mechanisms and installation techniques. A case study has been carried out where stone columns are designed according to given bore log data.

***Index Terms*—Stone Column, Ground Improvement, bearing capacity**

I. INTRODUCTION

India has large coastline exceeding 6000kms. In view of the developments on coastal areas in the recent past, large number of ports and industries are being built. In addition, the availability of land for the development of commercial, housing, industrial and transportation, infrastructure etc. are scarce particularly in urban areas. This necessitated the use of land, which has weak strata, wherein the geotechnical engineers are challenged by presence of different problematic soils with varied engineering characteristics. Many of these areas are covered with thick soft marine clay deposit, with very low shear strength and high compressibility. Although the use of pile foundation can meet all the design requirements, negative drag force and large length of the pile often result in prohibitive costs. On the other hand, ground improvement techniques are normally preferred for economical considerations.

Out of several techniques available, stone columns (also known as granular column or granular pile) have been widely used. This ground improvement technique has been successfully applied to increase the bearing capacity and to reduce the settlement for foundation of structures like liquid storage tanks, earthen embankments, raft foundations, etc., where a relatively large settlement is permissible. Stone columns have also been used to improve slope stability of embankments on soft ground. In spite of the wide use of stone columns and developments in construction methods and equipments, present design methods are empirical and only limited information is available on the design of stone columns in codes and textbooks. The stone column technique was adopted in European countries in the early 1960s and thereafter it has been used successfully. Ground improvement is used to address a wide range of geotechnical engineering problems, including but not limited to are Improvement of soft or loose soil to reduce settlement, increase bearing resistance, and/or to improve overall stability for structure and wall foundations and/or for embankments, To mitigate liquefiable soils, To improve slope stability for landslide mitigation, To retain otherwise unstable soils, To improve workability and usability of fill materials, To accelerate settlement and soil shear strength gain.

The main objective of the ground improvement is to improve the characteristics of the soil at the site. It usually consists of increasing the shear strength and decreasing the compressibility of the soil so that the bearing capacity of the soil is increased and the settlements of the structures built on it are reduced.

II. LITERATURE REVIEW

Several researchers have worked on theoretical, experimental and field study on behavior of stone columns. However very little information is available on design procedure that can be used for a given situation. Semi empirical design approach based on the allowable stress on stone columns and the undrained shear strength of clay have been proposed by Greenwood (1970),Hughes and Withers (1974), Saha (1992,1999). Semi empirical design approach based on pressuremeter theory was proposed by Hughes et al (1975). Cavity expansion approach proposed by Vesic (1972) have been used by Ranjan and Rao(1986) and Datye and Nagaraju(1981).In experimental approach, Hughes and Withers(1974) carried out series of model tests in normally consolidated clay. The test results indicated that ultimate capacity of stone column was governed primarily by the maximum radial reaction of the soil against the bulging and the extend of vertical movement in the stone column was limited to about 4 times the diameter. Shankar and Shroff (1997) conducted experimental studies to study the effect of pattern of installation of stone columns and showed that triangular pattern seems to be optimum and rational. Mitra and Chatopadhyay (1999) studied the effect of different factors influencing the capacity of stone column improved ground from the available literature and showed that in the case of columns failing by bulging the critical length is about 3 to 5 times the stone column diameter. Mitchell and Huber (1985) compared the field performance of stone columns with the predictions byfinite element analysis and reported that the agreement was generally good. It was concluded further that settlement predictions using other simpler methods also gave values, which agreed reasonably with the measured values.

Madhav (2000) presented an overview of recent contributions for the analysis and design of stone columns. Stone columns in compressive loads fail in different modes, such as bulging (Hughes and Withers 1974 Hughes et al. 1976), general shear failure (Madhav and Vitkar 1978), and sliding (Aboshi et al. 1979). Many of the researchers have developed theoretical solutions for estimating bearing capacity and settlement of reinforced foundationsby stone columns (Greenwood 1970; Hughes et al. 1976; Madhav and Vitkar 1978; Aboshi et al. 1979). A homogenization assumption (improved soil is assumed as a homogeneous material with equivalent properties) to estimate the ultimate bearing capacity and settlement is presented by Jellali et al. (2005).

Priebe (1995) proposed a method to estimate the settlement of foundation resting on the infinite grid of stone columns based on unit cell concept. In this concept, the soil around a stone column for area represented by a single column, depending on column spacing, is considered for the analysis. As all the columns are simultaneously loaded, it is assumed that lateral deformations in soil at the boundary of unit cell is zero. The settlement improvement factor is derived as a function of area ratio and angle of internal friction of column material. Except near the edges of the loaded area, the behavior of all column soil units is the same and thus only one column soil unit needs to be analyzed (Balaam et al.1978). The unit cell concept has also been used by Abhijit and

Das (2000), Goughnour (1983), and Sathish et al. (1997). Field observations showed that stone columns could also accelerate the rate of consolidation of soft clays (Han and Ye 1992). Han and Ye (2001) developed a simplified and closed form solution for estimating the rate of consolidation of the stone column reinforced foundations accounting for the stone column soil modular ratio. It is also reported in the paper that during the process of consolidation the stress on stone column increases with time, whereas the stress on soil decreases. At the end of consolidation, a steady stress concentration ratio is approached. The stone column improves the ground mainly due to the higher stiffness of the columns compared to the soil. Hence the most critical factor which controls the design of the stone column improved ground is the stiffness of the column and load sharing between column and soil. Hence in the present work an attempt is made to fully understand the design procedure considering the load sharing between column and soil.

II. Stone Columns As Ground Improvement Technique

The use of stone columns as a ground improvement technique is of recent origin. The method is generally adopted in clayey soils. The primary purpose of soil improvement by stone column technique is mainly to increase the bearing capacity of foundation soil and also to reduce post construction settlement. Stone columns are constructed by making holes in the deposit and filling these holes with gravel (or small stones) of size 6 to 100 mm. Stone columns act as vertical drains, increasing rate of consolidation. They reinforce the soft soil deposit because the soft soil is replaced by strong stone columns at discrete points. This action is somewhat similar to that of vertical steel bars in a R.C.C column. The stiffness of the stone columns is very large as compared to that of the soft soil nearby, a large portion of the superimposed load is carried by stone columns.. Thus the bearing capacity of the clay deposit is increased and the settlements are reduced.

This method can be treated as the extension of technique of densification of cohesionless soils by vibroflot. Earlier stone columns were formed by vibroflot but now they are formed by forming a bore as in bored cast-in-situ concrete piles. The method has been mainly used to improve subsoil below buildings, embankments etc. In recent years, stone columns have also been used in prebored holes by compacting the granular fill material by a rammer. This method has been developed in India and has been gaining importance in Indian practice. In this method ordinarily bored piling equipment is used. The details of the installation techniques and the performance of these granular piles are discussed in the following sections.

Important Features of Stone Column Treatment

Subsurface soils whose undrained shear strength ranges from 7 to 50 kPa or loose sandy soils including silty or clayey sands represent a potential class of soils requiring improvement by stone columns. Subsurface conditions for which stone columns are in general not suited include sensitive clays and silts (sensitivity is 2.4) which lose strength when vibrated and also where suitable bearing strata for resting the toe of the column is not available under the weak strata.

The disturbance caused to the soil mass due to a particular method of constructing the stone columns significantly affects the overall behaviour of the composite ground. The availability of equipment, speed of construction and the depth of treatment would normally influence the choice of construction technique.

The treatment depth with stone column for a given soil profile should be so determined that the stone columns extend through the most significant compressible strata that contribute to the settlement of the foundation. Average depth of stone column accomplished in India may be around 15.0 m or so, although with equipment modification, higher depths beyond 20 m may become a possibility in future.

Stone columns work most effectively when used for large area stabilization of the soil mass. Their application in small groups beneath building foundations is limited and is not being used. Thus, large loaded areas which apply uniform loading on foundation soils, such as beneath embankments, tank farms and fills represent a major area of application.

End bearing is not a specific requirement for stone columns. However, they should extend through the soft compressible strata. The soil near the ground surface has a dominating influence on settlement and ultimate bearing capacity of stone columns.

Soil-Column Interaction

Stone columns are stiffer than the in-situ soil they replace. Because the column is cohesion less, its stiffness depends upon the lateral support given by the soil around it. If that support is inadequate, the column fails by bulging. The stability of a soil- column composite system also depends on whether shear action (skin friction) develops between the column and the soil surrounding it. For instance, if the footing load is applied to the column alone leaving the surrounding ground unloaded, or if the column is forced to settle at the top unevenly with the surrounding soil under the influence of a wide-loaded area, shear forces may be induced along the column at the column soil interface. In such cases, a column may fail as a pile because of insufficient skin friction and end bearing. Stone columns should be analyzed for both modes of failure-bulging or shear (Greenwood and Kirsch, 1984).

Soft compressible soils undergo much lower settlements when they are stiffened by stone or sand columns. Bulging of the column under the load causes horizontal compression of the soil between columns which provides additional confinement for the stone. An equilibrium is eventually reached resulting in reduced vertical movement when compared to unreinforced soil. Because the rigidity of the stone column is substantially higher than that of the surrounding soil, a larger portion of the applied load is transferred to the stone. A blanket of sand and gravel or a semi-rigid mat of reinforced earth is usually placed above the stone column-reinforced soil. This mat facilitates transfer of superimposed loads to the stone columns by arching over the in-situ soil. with time, as the surrounding clay consolidates, further load transfer takes place from the native soil to the stone columns by negative friction resulting in additional reduction in soil settlement (Munfakh et al. 1984).

Hughes, et al. (1976) defines a critical length for an isolated stone column considering the column as a pile. Beyond that length, the column does not contribute extra benefit in terms of bearing capacity but it continues to reduce settlement by penetrating to a firmer layer. With typical soil and column parameters, the critical depth is usually about four column diameters (Mattes and Poulos, 1969).

Basic Design Parameters

In stone column construction, usually 15 to 35 percent of the weak soil volume is replaced by stone. Design loads on stone columns typically vary from 20 to 50 tons. The presence of the column creates a composite material of lower overall compressibility and higher shear strength than the native soil alone. Confinement, and thus stiffness of the stone, is provided by the lateral stress within the weak soil. Upon application of vertical stress at the ground surface, the stone and weak soil move downward together resulting in an important concentration of stress within the stone column. The resulting stress concentration in the stone is primarily due to the column being stiffer than the soil.

Stone Column Diameter (d)

The column diameter is dictated by the desired level of improvement, the method of installation, the stone size and the strength of the in-situ soil. Reported column diameters range from 1.5 ft. (0.45 m) to 4.0 ft. (1.2 m). Besancon et al. (1984) developed a graphical correlation between the column diameter and the undrained shear strength of the soil using actual reported case applications. The lower portion of their proposed graphical band corresponds to stone columns constructed using less than 40-mm size material while the upper portion represents columns with materials up to 100-mm in size.

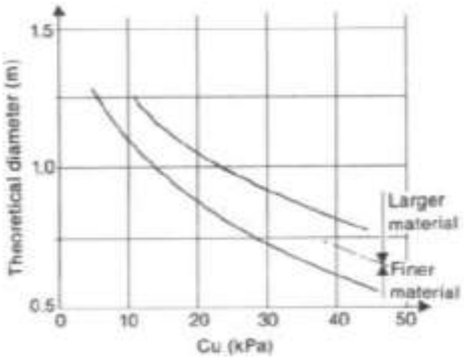
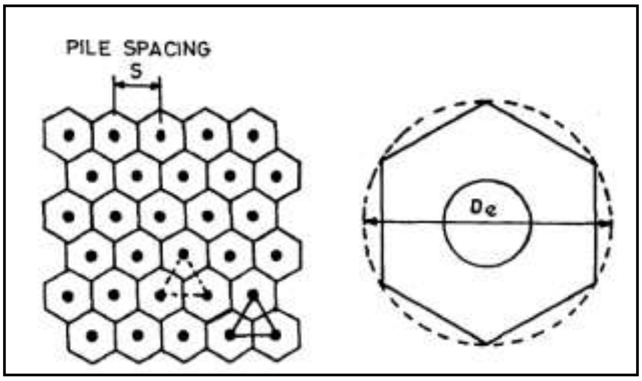


Fig 1 - Effect of Soil Strength On Theoretical Column Diameter

Installation of stone columns in soft cohesive soils is basically a self compensating process that is softer the soil, bigger is the diameter of the stone column formed. Due to lateral displacement of stones during vibrations/ramming, the completed diameter of the hole is always greater than the initial diameter of the probe or the casing depending upon the soil type, its undrained shear strength, stone size, characteristics of the vibrating probe/rammer used and the construction method.

Pattern of Columns

Stone columns can be installed in a triangular arrangement or a square shaped arrangement. Stone columns are constructed usually in an equilateral triangular pattern although a square pattarn is sometimes used. The equilateral triangle pattern gives the most dense packing of stone columns in a given area. A typical layout of stone columns in an equilateral triangular pattern is shown in Fig.



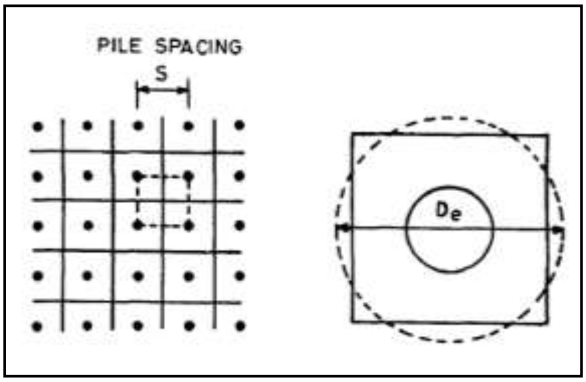


Fig 2 - Triangular Arrangement of Stone Columns

Fig 3- Square Arrangement Of Stone Columns

Spacing of Columns (s)

The design of stone columns should be site specific and no precise guidelines can be given on the maximum and the minimum column spacing. However, the column spacing may broadly range from 2m to 3m depending upon the site conditions, loading pattern, column factors, the installation technique, settlement tolerances, etc. For large projects, it is desirable to carry out field trials to determine the most optimum spacing of stone columns taking into consideration the required bearing capacity of the soil and permissible settlement of the foundation.

Equivalent Diameter (De)

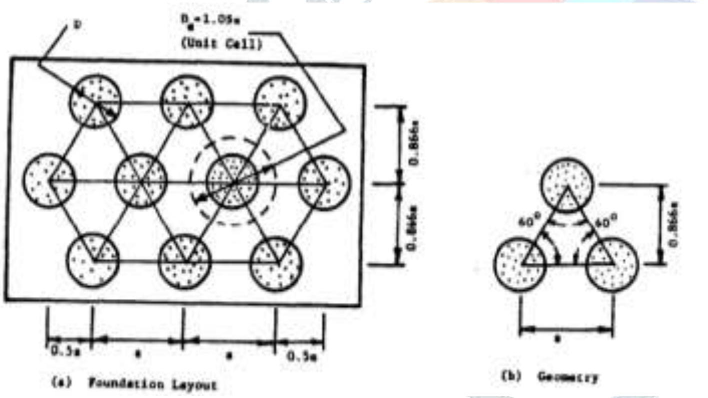
For purposes of settlement and stability analyses, it is convenient to associate the tributary area of soil surrounding each stone column with the column as illustrated in Figs. 4. Although the tributary area forms a regular hexagon about the stone column, it can be closely approximated as an equivalent circle having the same total area. The equivalent circle has an effective diameter (De) which is given by following equation:

De = 1.05 S …for an equilateral triangular pattern, and

= 1.13 S …for a square pattern

where,

S = spacing of the stone columns.



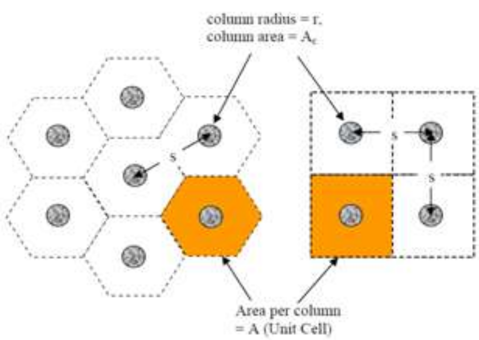


Fig 4 - Equilateral Triangular Pattern of Stone Columns

Fig 5- Unit Cell Idealization

The resulting equivalent cylinder of composite ground with diameter De , enclosing the tributory soil and one stone column is known as the unit cell, as shown in fig. 5

Replacement Ratio (as)

The composite ground representing an infinitely wide loaded area may be modeled as a unit cell comprising the stone column and the surrounding tributory soil. The volume of soil replaced by stone columns has an important effect upon the performance of the improved ground. To quantify the amount of soil replaced by the stone, the term, replacement ratio, as is used.

Replacement ratio (as) is given by :

as= As/ A = As / (As + Ag)

where

As = area of the stone column,

Ag = area of ground surrounding the column,

A= total area within the unit cell.

The area replacement ratio may also be expressed as follows:

as = 0.907 (D/S)2

where the constant 0.907 is a function of the pattern used which, in this case, is the commonly employed equilateral triangular pattern.

Stress Concentration Factor (n)

Stress concentration occurs on the stone column because it is considerably stiffer than the surrounding soil. From equilibrium considerations, the stress in the stiffer stone columns should be greater than the stress in the surrounding soil. The stress concentration factor (n) due to externally applied load σ, is defined as the ratio of average stress in the stone column, σs, the stress, σg, in the soil within the unit cell.

$$n = (\sigma s / \sigma g)$$

The value of n generally lies between 2.5 and 5 at the ground surface. The stress concentration factor, n, increases with time of consolidation and decreases along the length of the stone column. Higher n value at ground surface may result if load is applied to the composite ground through a rigid foundation as compared to the flexible foundation.

The stress concentration factor, n, may be predicted using elastic theory as a function of the modular ratio of the stone and the clay assuming equal vertical displacements. However, as the modular ratio can vary within wide limits, it should be selected from the above given equation.

IV. FAILURE MECHANISMS

Single Stone Columns

Stone columns may be constructed as either end bearing on a firm stratum underlying soft soil, or as floating columns with the tip of the column embedded within the soft layer. In practice, however, end bearing stone columns have almost always been used in the past.

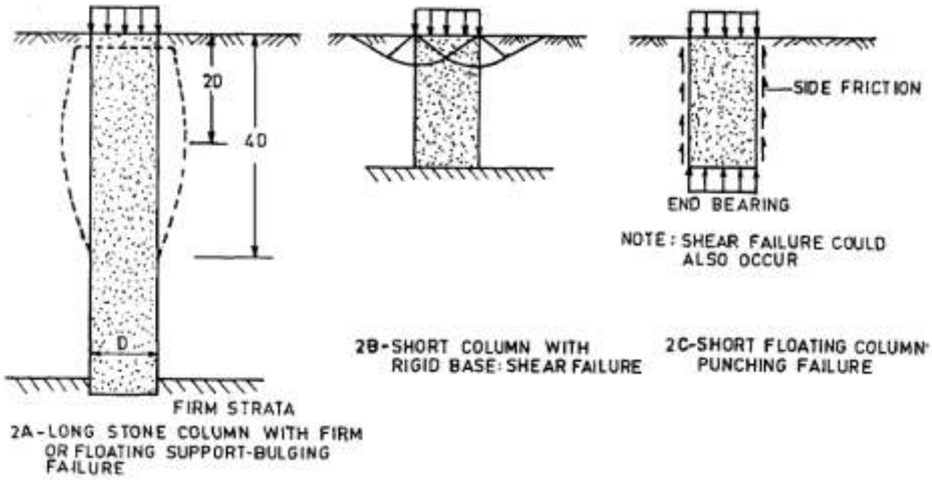


Fig 6 -Failure Mechanisms of A Single Stone Column In A Homogeneous Soft Layer

Failure mechanism of a single stone column loaded over its area significantly depends upon the length of the column. Consider a stone column loaded over just the area of the column. Either end bearing or free floating stone columns greater than about four diameters in length fail in bulging as illustrated in (Fig. 6). However, column shorter than the critical length bearing on a firm support is likely to fail in general (Fig 2B). Finally, a floating stone column less than about 2 to 3 diameters in length may fail in end bearing in the weak underlying layer before a bulging failure can develop (Fig. 2C). For the subsurface conditions generally encountered in practice, however, bulging is usually the controlling failure mechanism.

In practice, however, a stone column is usually loaded over an area greater than its own (Fig. 7) in which case it experiences significantly less bulging leading to greater ultimate load capacity and reduced settlements since the load is carried by both the stone column and the surrounding soil.

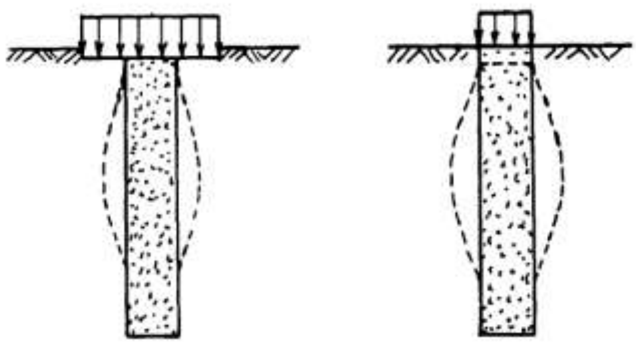
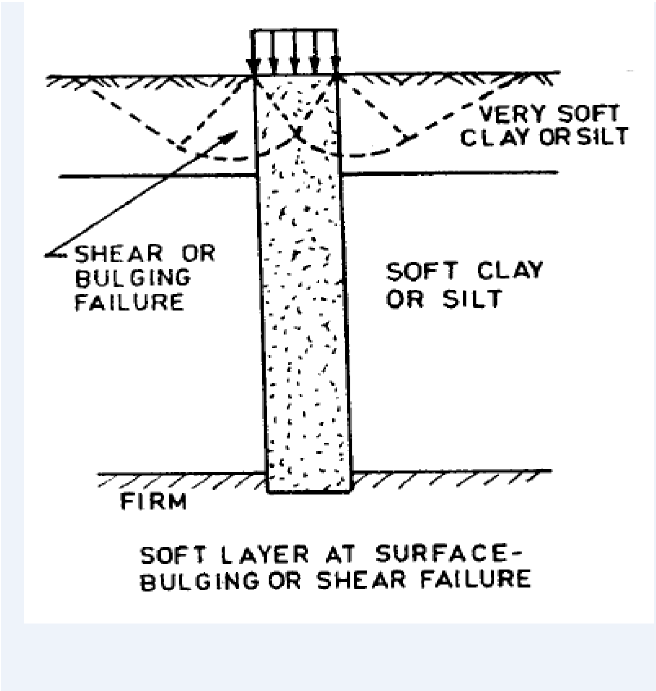


Fig 7 - Different Type of Loadings Applied to Stone Columns

The above failure mechanisms apply to stone columns installed in homogeneous soils. Practical situations may arise where isolated zones of very soft cohesive soils may result in significant bulging at both shallow and deep depths and hence, this should be duly considered wherever necessary.

When interlayering of sand and clay occurs, and if the sand layer is thick enough as compared to the size of the loaded area, the general compaction achieved by the action of the installation of the stone columns may provide adequate rigidity to effectively disperse the applied stresses thereby controlling the settlement of the weak layer. However, effective reduction in settlement may be brought about by carrying out the treatment of stone columns through the compressible layer.

When clay is present in the form of lenses and if the ratio of the thickness of the lense to the stone column diameter is less than or equal to 1, the settlement due to presence of lenses maybe insignificant.



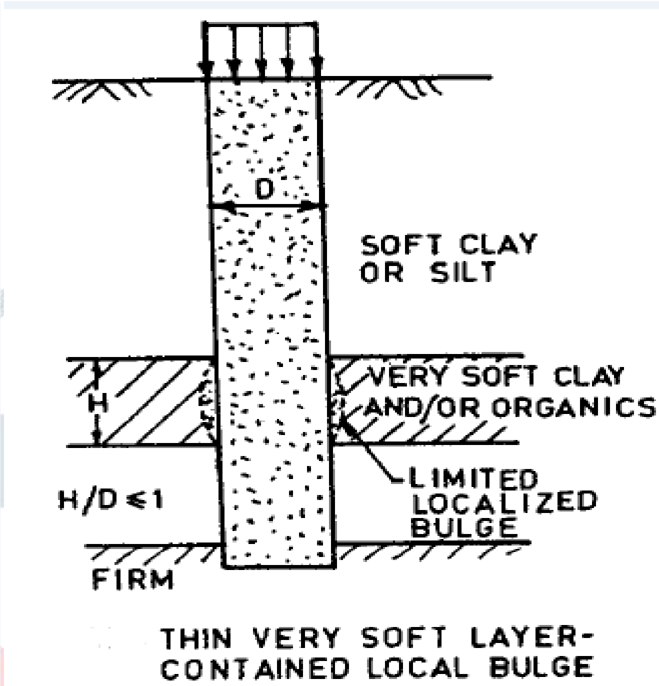


Fig 8 -Failure Mechanisms In Non-Homogenous Cohesive Soil Fig 9 - Failure Mechanisms In Non-Homogenous Cohesive Soil

Stone Column Groups

An isolated single column compared to a stone column group has a slightly smaller ultimate load capacity per column than in the group. As surrounding columns are added to form a group, the interior columns are confined and hence somewhat stiffened by the surrounding columns. This results in a slight increase in the ultimate load capacity per column.

A group of stone columns in a soft soil probably undergoes a combined bulging and local bearing. A local bearing failure is the punching of a relatively rigid stone column (or group) into the surrounding soft soil. Stone column groups having short column lengths can fail in end bearing or perhaps undergo a bearing capacity failure of individual stone columns similar to the failure mode of short, single stone columns.

Consider a wide flexible loading such as an embankment constructed over a stone column improved ground. Vautrain has found the settlement of the compressible soil and stone column to be approximately equal beneath an embankment. Due to the construction of the embankment over the weak foundation, the soil beneath and to the asides of the foundation move laterally outward. This phenomenon is called "spreading".

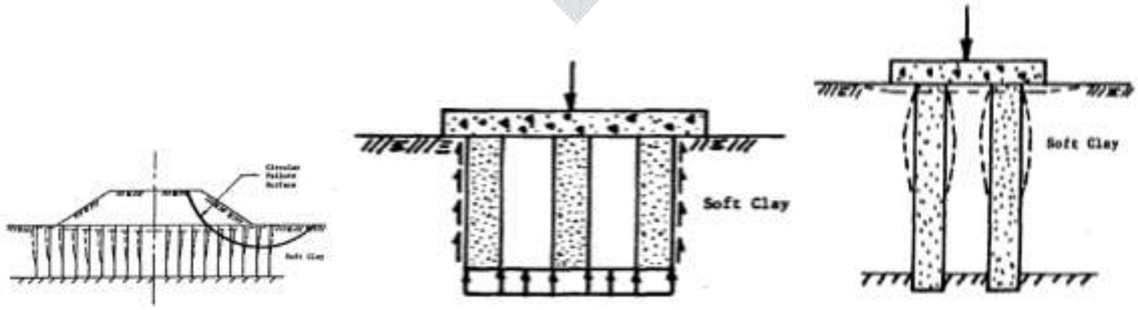


Fig 10 - Failure Modes of Stone Column Groups.

V. Installation Techniques

Non Displacement Method

Bailer and Casing Method

In this method, the borehole is advanced by using a bailer while its sides are retained by a casing. To minimize disturbance at the bottom of the hole and to avoid loss of ground due to suction, the water level in the casing should be maintained at around 2.0 m above the surrounding ground water level.

To avoid suction effects, the bailer diameter should be 75 mm to 100 mm less than the internal diameter of the casing. Driving of casing and advancing of boring by bailer should be done alternately to progress the cased borehole without endangering the adjacent stone column already installed.

At commencement of boring, a guide boring of 0.5 m to 1.0m depth should be drilled with bailer in order to properly support the casing within the borehole to facilitate driving by bailer. Sectional lengths of the casing are added on till the desired depth of treatment has been reached.

When the casing has reached the desired depth of the column, chemically inert, sound and well graded crushed rock of 75 mm down to 2 mm is placed in the casing to fill it to about 1m to 1.5 m depth.

After placement of this charge, the casing is withdrawn making sure that its bottom invariably remains a minimum of 0.5 m into the aggregate.

The loose charge below the bottom of the casing is then compacted by operating a rammer of suitable weight and fall within the casing so as to obtain a ramming energy of around 20 KNm (Joules) per blow. The extent of ramming is measured by the set criterion, that is, by measuring penetration of the rammer into the backfilled material or a given number of blows. For the rammer system proposed to be used, the set criterion would be established individually for each site by conducting appropriate field trials. Although the set will be governed by the rammer input energy as well as the fill characteristics, a satisfactory compaction is considered to be achieved when a set of 10 mm or less is obtained for the last 5 blows using rammer energy.

The procedure is repeated till a stone column of the desired length has been formed.

Direct Mud Circulation (DMC) Method

In this method, the borehole walls may be stabilized with bentonite mud. However, prior to putting in the stone charge, a casing of suitable diameter is lowered to the bottom of the borehole, bentonite mud completely pumped out and the same is replaced with clean water. Backfilling of the hole with stone charges and their compaction in stages is done in the same manner as described in the above method. For formation of a stone column of an acceptable quality column of water in the excavated hole should be kept clear of suspended/settled impurities.

Rotary Drill Method

In this method, boring is performed with rotary equipment employing augers or buckets. The borehole sides may be stabilized using a casing or alternatively, by using bentonite mud as per direct mud circulation method. Driving of casing to stabilize the boreholes sides, pouring of stone charge and compaction of the same is done in the same manner as in bailer and casing method.

DISPLACEMENT METHODS

Vibro-Replacement Method

In this method, creation of hole in the ground and compaction of granular fill backfilled in the hole is accomplished mechanically using a vibratory unit called vibrofloat. Stone columns may be constructed using this equipment either by:

a) Wet process — Generally suitable for soft to firm soil with high water table condition where borehole stability is questionable, or

b) Dry process — Suitable for soils of relatively high initial strength with relatively low water table where the hole can stand of its own upon extraction of the probe, such as unsaturated fills.

Vibroflot

The vibroflot is a poker vibrator normally of diameter ranging from 300 mm to 450 mm and about 2 m to 3.5 m long. It weighs 2 t to 4 t depending upon the size. Several versions of the vibroflot may be available with respect to its diameter, length and weight. Specialist opinion may be sought for an appropriate selection of the equipment after giving due consideration to the soil type, its strength characteristics, depth of treatment, etc.

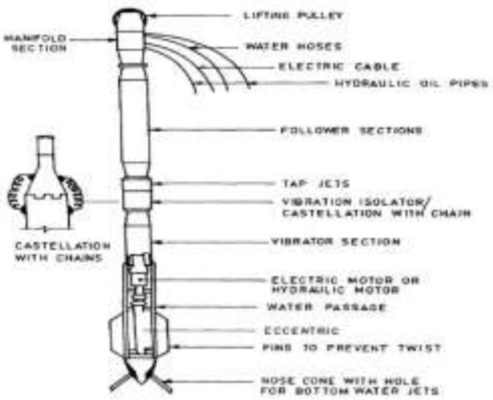


Fig.11 Essential Features of Vibrofloat

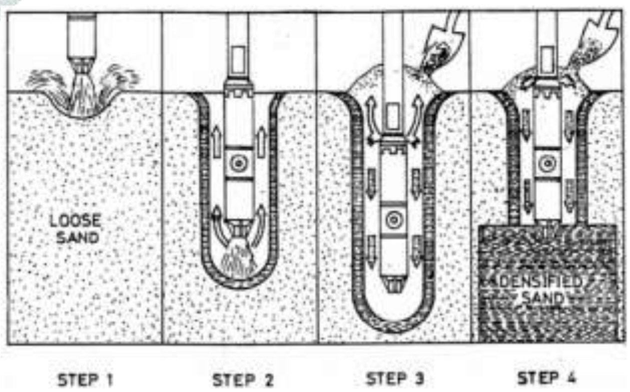


Fig. 12 Vibrofloatation Compaction Process

VI. Design Of Stone Columns

Design Considerations

By assuming a triaxial state of stress in the stone column and both the column and the surrounding soil at failure, the ultimate vertical stress, $\sigma 1$, which the stone column can take may be determined from the following equation:

$$\frac{\sigma_1}{\sigma_3} = \frac{1 + \sin \phi_s}{1 - \sin \phi_s}$$

where

σ_3 = lateral confining stress mobilized by the surrounding soil to resist the bulging of the stone column

ϕ_s = angle of internal friction of the stone column and

σ_1/σ_3 = coefficient of passive earth pressure k_p of the stone column.

This approach assumes a plane strain loading condition (such as passive resistance mobilized behind a long retaining wall) and hence does not realistically consider the three dimensional geometry of a single stone column. The bearing capacity of an isolated stone column or that located within a group maybe computed using the other established theories also. Besides the passive resistance mobilized by the soil, the increase in capacity of the column due to surcharge should be taken into consideration, In addition capacity increase due to soil bearing should also be taken into account. Particular attention should be paid to the presence of very weak organic clay layers of limited thickness where local bulging failure may take place (see Fig.5.4). Therefore, capacity of column in such weak clays should also be checked even if they are below the critical depth.

Adjacent Structures

When working near existing structures, care should be taken to avoid damage to such structures by suitable measures. In case of deep excavation adjacent to stone columns, prior shoring or other suitable arrangement should be done to guard against the lateral movement of soil or loss of confining soil pressure.

Ultimate Load Capacity and Settlement

The ultimate load carrying capacity of stone column may be estimated approximately on the basis of soil investigation data or by test loading. However, it should be preferably determined by an initial load test on a test column specifically installed for the purpose and tested to its ultimate load particularly in a locality where no such previous experience exists. Procedure for estimating the load capacity and settlement of a single column has been discussed in further sections.

Environmental Factors

Design considerations should take into account the environmental factors, such as presence of aggressive chemicals in the sub-soil and ground water, an artesian safety recommended in each formula should be conditions, etc. applicable.

Load Test Results

The ultimate load capacity of single column may be determined from load tests with reasonable accuracy. The settlement of a stone column obtained at safe/ working load from load test results on a single column should not be directly used in forecasting the settlement of the structure unless experience from similar foundations in similar soil conditions on its settlement behaviour is available.

Factor of Safety

It is desirable that the ultimate capacity of column is obtained from an initial load test. The minimum factor of safety for such a load test should be 2.5. When ultimate capacity is derived from soil mechanics considerations, the minimum factor of safety recommended in each formula should be applicable.

Estimation of Load Capacity Of Stone Column

Load capacity of the treated ground may be obtained by summing up the contribution of each of the following components for wide spread loads, such as tankages and embankments:

a) Capacity of the stone column resulting from the resistance offered by the surrounding soil against its lateral deformation (bulging) under axial load.

b) Capacity of the stone column resulting from increase in resistance offered by the surrounding soil due to surcharge over it.

c) Bearing support provided by the intervening soil between the columns.

Capacity Based on Bulging of Column

Considering that the foundation soil is at failure when stressed horizontally due to bulging of stone column, the limiting (yield) axial stress in the column is given by the sum of the following:

$$\sigma_v = \sigma_{rL} \times Kp_{col}$$

$$\sigma_v = (\sigma_{ro} \times 4C_u)\, Kp_{col}$$

where

σ_v = limiting axial stress in the column when it approaches shear failure due to bulging .

σ_{rL} = limiting radical stress

$= \sigma_{ro} + 4C_u$

where

C_u = undisturbed undrained shear strength of clay surrounding the column, and

σ_{ro} = initial effective radial stress

$= K_o \times \sigma_{vo}$

where

K_o = average coefficient of lateral earth pressure for clays equal to 0.6 or alternatively, as determined from the relationship = l-sin , where @is the effective angle of internal friction of soil

σ_{vo} = average initial effective vertical stress considering an average bulge depth as 2 times diameter of the column. $\sigma_{vo} = \gamma 2D$.

where

γ = effective unit weight of soil within the influence zone.

$Kp_{col} = \tan^2(45° + \phi_c/2)$

where

ϕ_c = angle of internal friction of the granular column material and it may vary depending upon angularity, surface characteristics and density of column material. Value applicable for the stones intended to be used as backfill material may be determined using large shear box tests or laboratory shear test. In absence of such tests, the design may be based on the best engineering judgement. As a broad guide, the ϕc may range from 38° to 42° depending upon the compactness achieved during construction of stone columns.

Yield load = $\sigma_v \times \pi/4\ D^2$

Safe load on column alone Q_1 = (Yield Load)/2 …….(1)

where

2 is the factor of safety

Capacity Based on Surcharge Effect

Initially, the surcharge load is supported entirely by the rigid column. As the column dilates some load is shared by the intervening soil depending upon the relative rigidity of the column and the soil. Consolidation of soil under this load results in an increase in its strength which provides additional lateral resistance against bulging. The surcharge load may consist of sand blanket and sand pad (being applicable to tank foundations). If thicknesses of these elements are not known, the limiting thickness of the surcharge loading as represented by the safe bearing capacity of the soil may be considered.

The increase in capacity of the column due to surcharge may be computed in terms of increase in mean radial stress of the soil as follows:

$\Delta\sigma_{ro} = (q_{safe}\ (1 + 2K_o))/\ 3$

where

$\Delta\sigma_{ro}$ = is the increase in mean radial stress due to surcharge, and q_{safe} is the safe bearing pressure of soil with the factor of safety of 2.5.

$q_{safe} = C_u\ N_c/2.5$

Increase in ultimate cavity expansion stress = $\Delta\sigma_{ro} \times F_q$

where

F_q = vesic's dimension less cylindrical cavity expansion factor

$F_q = 1$ for $\phi_g = 0$

Increase in yield stress of the column = $Kp_{col} \times \Delta\sigma_{ro}$

Allowing a factor safety of 2, increase in safe load of column, Qj is given by the following formula:

$Q_2 = (\Delta\sigma_{ro}\ Kp_{col}\ A_s)/2$ …….(2)

The surcharge effect is minimum at edges and it should be compensated by installing additional columns in the peripheral region of the facility.

Bearing Support Provided by the Intervening Soil

This component consists of the intrinsic capacity of the virgin soil to support a vertical load which maybe computed as follows:

Effective area of stone column including the intervening soil for triangular pattern = 0.866 S2

Area of intervening soil for each column, Ag is given by the following formula:

$$A_g = 0.866\ S^2 - \frac{\pi\ D^2}{4}$$

Safe load taken by the intervening soil, $Q_3 = q_{safe} \times A_g$ ……(3)

Overall safe load on each column and its tributory soil = $Q_1 + Q_2 + Q_3$

Determination of Column Spacing (S)

From the plan area of the structure and the number of columns as assessed. The number of columns to be provided under a structure may be obtained if the total load to which the structure is subjected to and the reduction in settlements required considering the permissible total and differential settlements for it are known. This, in turn, will lead to effective spacing between the columns depending pattern of columns as follows:

Pattern	Area for Column
Triangular	$0.866\ S^2$
Square	$1.0\ S^2$

Design calculations should be repeated till there is convergence of the assumed and the calculated column spacing. One or two trials may be required to achieve an acceptable degree of convergence. Additional stone columns may be required inside and outside the periphery of the loaded area considering pressure distribution, presence/absence of surcharge and permissible or expected settlement of the structure. These additional columns may be provided either as rings or at a closer spacing for an appropriate distance inside as well as outside the periphery of the loaded area.

VII. REINFORCED STONE COLUMNS

The use of stone columns has proved to be an economical and technically viable ground improvement technique for construction on soft soils. When the stone columns are installed in very soft clays, they may not derive significant load capacity due to low lateral confinement, which leads to excessive bulging. The geotextile encased columns and geogrid encased stone column (GESC) system, which increases the confinement effect, has been developed to improve the load carrying capacity of stone columns. It is found that reinforced stone columns have much higher load carrying capacity and less lateral bulging compared to conventional stone columns.

Reinforced Stone Columns

The stone column technique was adopted in European countries in the early 1960s and thereafter it has been used successfully. Stone columns in compressive loads fail in different modes, such as bulging (Hughes and Withers 1974), general shear failure (Madhav and Vitkar 1978), and sliding (Aboshi et al. 1979). A long stone column having a length greater than its critical length i.e., about 4 times the diameter of the column, it fails by bulging irrespective of whether it is end bearing or floating. McKelvey et al. (2004) carried out experimental studies on a group of five stone columns and reported that the central column deformed or bulged uniformly, whereas the edge columns bulged away from the neighboring columns.

To overcome these limitations, and to improve the efficiency of the stone columns with respect to the strength and the compressibility, stone columns are encased (reinforced) using geogrids /geocomposites. Deshpande & Vyas (1996) have brought out conceptual performance of stone columns encased in geosynthetic material. Katti et al (1993) proposed a theory for improvement of soft ground using stone columns with geosynthetic encasing based on the particulate concept. The foundation system with geotextile/ geogrid encased sand or a gravel column (GEC) is a new soil improvement method which is an extension of the well known stone column and sand compaction pile foundation improvement techniques. The only difference is that the column in this new method is encased with geotextile of high tensile strength.

Geotextile Encased Columns

The foundation system 'Geotextile-Encased Columns' (GEC) is a further development of well-known column foundations such as vibro displacement piles and granular piles. In contrast to conventional column foundations, encased columns can also be used as a ground improvement and bearing system in very soft soils, for example peat or sludge (undrained shear strength cu < 5 kN/m²). As opposed to conventional stone column foundations, geotextile-encased sand or

gravel columns can be used as a ground improvement method for very soft soils. With a non-encased column, the horizontal support of the soft soil must be equal to the horizontal pressure in the column. With a geotextile-encased column, the horizontal support of the soft soil can be much lower, due to the radial supporting effect of the geotextile casing. The horizontal support depends also on the vertical pressure over the soft soil, which can be much smaller. As a result we get a stress concentration above the column head and a lower vertical pressure over the soft soil and therefore a large settlement reduction. To withstand the high ring tension forces, these geotextile casings are manufactured seamlessly. The columns act simultaneously as vertical drains, but the main effect is the transport of the load to a deeper bearing layer. Geotextile is preferrable over geogrid as it provides the multiple function of separation, drainage and reinforcement. Geotextile does not restrain the lateral or vertical movement as it can maintain the strain compatibility with soil within serviceable limit of 5%.

Appropriate selection of the geotextile fibre enables the columns to be used in chemically aggressive grounds, where for example uncased stone or concrete columns would have a limited life. Finally, geotextile encased columns have intrinsic flexibility and can support dynamic loads (e.g. from trains so that they are suitable for supporting railway embankments) without damage. The advantages of using this technique include avoiding the need for excavating and disposing of unsuitable or even contaminated soil and minimising settlements taking place both during construction and in the longer term: these benefits result in cost savings and shorter construction times.

Geogrid Encased Stone Columns

The Geogrid Encased Stone Column (GESC) system, which increases the confinement effect, has been developed to improve the load carrying capacity of stone columns. Murugesan and Rajagopal (2006) investigated the qualitative and quantitative improvement in load carrying capacity of the stone column by encasement through a comprehensive parametric study using the finite element analysis. It is found from the analyses that the encased stone columns have much higher load carrying capacities and undergo lesser compressions and lesser lateral bulging as compared to conventional stone columns. The results have shown that the lateral confining stresses developed in the stone columns are higher with encasement.

The GEC method has been applied mainly to soft ground such as marine areas. It has the disadvantage of increasing construction cost because it uses sand as the filler, causing insufficiency of natural aggregate. By contrast, the geogrid-encased stone column method, which uses stones, waste concrete and recycled aggregates as the filler thus reducing the material cost. Partial encasement with a high strength geogrid is more economical because it reinforces the weak part of the stone column unlike the GEC method which reinforces the entire sand column with geotextile.

The GEC method, which is similar to the GESC, is suitable mainly to the seabed soft ground. It consists of the following procedure: Installation of the case for the installation of the geotextile, sand filling, case removal and then sand column installation. The GESC method consists of the following procedure: Installation of columns by using a casing to install the geogrid to prevent the outer wall from collapsing during drilling with consideration of the features of soft ground. The GESC method can reinforce only the upper part of the stone column.

Yoo (2010) presented the results of a numerical investigation into the performance of geosynthetic-encased stone columns installed in soft ground for embankment construction. The results indicated among other things that additional confinement provided by the geosynthetic encasement increases the stiffness of the stone column and reduces the degree of embankment load transferred to the soft ground, thereby decreasing the overall settlement. It was also shown that the geosynthetic encasement has a greater impact for cases with larger stone column spacing and/or weaker soil.

Stone Columns Reinforced Using Geogrid In Lateral Direction


Fig 13 Aggregates compacted without geogrid layes Fig 14 Aggregates compacted with geogrid inceted in layers

The use of stone columns has proved to be an economical and technically viable ground improvement technique for construction on soft soils. When the stone columns are installed in very soft clays, they may not derive significant load capacity due to low lateral confinement, which leads to excessive bulging. A new method of improving the performance of stone columns is being suggested by reinforcing the stone columns with Geogrids in lateral direction in layers. That is, when aggregates are compacted within a confinement, it collapses on removal of confinement. If geogrid is inserted at various intervals with aggregates filling in layers, aggregates retain their form and behave as a stable coherent gravity mas.

VIII. CONCLUSIONS

The rapidly increasing cost of construction and numerous environmental constraints often placed on a project have greatly encouraged the in-situ improvement of marginal sites. Stone columns are one method of ground improvement that offers, under certain conditions, an alternative to conventional support methods in both weak cohesive soils and also loose silty sands. For each ground improvement problem, however, all feasible design alternatives must be thoroughly evaluated before selecting the most cost effective method.

Applications

Stone columns have a wide range of potential applications. The following indicate a few of these applications:

1. Potential uses in highway construction include (a) embankment support over soft cohesive soils, (b) bridge approach fills, (c) bridge abutments, (d) widening and reconstruction work, (3) reduction in bridge length, (f) single span bridge support, (g) bridge bent and miscellaneous structural support.

2. Important applications of stone columns also exist for landslide stabilization and liquefaction problems involving bridge foundation and embankment support during earthquakes.

3. The support of a Reinforced earth retaining wall or abutment on stone columns gives a very flexible, compatible type construction, capable of withstanding relatively large movements. Reinforced earth walls have been supported on cohesive soils having shear strengths as low as 200 to 400 psf (10-20 kN/m2). For these very soft to soft soils, wall settlement has been on the order of 1 to 2 ft (0.3-0.6 m).

Stone Column Construction

Construction of stone columns was considered in detail in Chapters III, Stone columns are usually constructed using a vibrating probe often called a Vibroflot or Poker. In the wet process, the vibrator opens a hole by jetting using large quantities of water under high pressure. Because of the use of large quantities of water in the wet process, caution must be exercised to control from the environmental standpoint the water and silt from the construction process. In the dry process, which may utilize air, the probe displaces the native soil laterally as it is advanced into the ground. The dry process is used primarily for environmental reasons.

Inspection

Field inspection of stone columns is even more important than for conventional shallow or deep foundations. Important aspects of the vibro-replacement (wet) process requiring special attention during construction include (1) using a large quantity of water (about 3,000. to 4,000 gal/hr.,lo-14 m3/hr. average) at all times to maintain a stable hole and give a clean column, (2) in soft soils leaving the probe in the hole at all times with the jets running, (3) constructing the stone column in lifts no greater than 4 ft (1.2 m), and (4) to insure good densification, repenetrating each new lift with the vibrator several times and also achieving the required ammeter reading. The discovery during construction of any peat layers should be brought to the immediate attention of both the project and design engineers. Finally, detailed construction records should be kept and analyzed for changes in quantity of stone consumption and time to both jet the hole and form the stone column.

Subsurface Investigation and Testing

A thorough subsurface investigation and evaluation of geotechnical properties are essential for the design of stone columns and the selection of the most suitable design alternative. For sites underlain by firm to soft cohesive soils, use of field vane shear testing is recommended in the subsurface investigation. Care in the subsurface investigation should also be taken to identify organic and peat layers.. Field pumping tests should be performed where a reliable estimate of the time rate of settlement is required for the success of the project, or for reliable comparisons of different design alternatives. On routine projects laboratory perneability tests on vertical and horizontal samples can be used to evaluate the consolidation characteristics.

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